# Phoenix Mars Scout UHF Relay-Only Operations

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**The Phoenix Mars Scout Lander will launch in August 2007 and land on the northern plains of Mars in May of 2008. In a departure from traditional planetary surface mission operations, it will have no direct-to-Earth communications capability and will rely entirely on Mars-orbiting relays in order to facilitate command and control as well as the return of science and engineering data. The Mars Exploration Rover missions have demonstrated the robust data-return capability using this architecture, and also have demonstrated the capability of using this method for command and control. The Phoenix mission will take the next step and incorporate this as the sole communications link. Operations for 90 Sols will need to work within the constraints of Odyssey and Mars Reconnaissance Orbiter communications availability, anomalies must be diagnosed and responded to through an intermediary and on-board fault responses must be tolerant to loss of a relay. These and other issues pose interesting challenges and changes in paradigm for traditional space operations and spacecraft architecture, and the approach proposed for the Phoenix mission is detailed herein.**

## I. Introduction

RELAY missions are not a new idea. The Gallileo probe, the Cassini-Huygens probe, and the Deep Impact "Impactor" relied on relay of their data via their "mother spacecraft." Even the Space Shuttles and the Hubble Space Telescope make use of the Tracking and Data Relay Satellite System (TDRSS) to relay many aspects of their mission data. Relay missions to Mars are familiar territory as well. The Viking Landers relayed much of their science data via 16Kbps UHF links and even Entry Descent and Landing 2Kbps data to the Viking Orbiters overhead (similar to the MER approach)[1]. The Sojourner rover received its commands and relayed data back to the Mars Pathfinder (MPF) Lander via a short-range relay link. The ill-fated Beagle lander was to have been entirely controlled through the Mars Odyssey (initially) and the Mars Express Orbiters. The Mars Exploration Rover (MER) missions have demonstrated just how valuable a high-bandwidth return link via relay can be as they continue to explore Gusev and Meridianni[2]. Even to this mission, the Phoenix Mars Scout Lander[3, 4], the concept of a relay is not new. In the Phoenix Lander's original incarnation as the Mars Surveyor Program 2001 (MSP '01) Lander, it was to have an all-relay landed mission using the Mars Climate Orbiter (MCO) and its twin-spacecraft, Mars Odyssey 2001 Orbiter (Odyssey) to achieve its command and control; additional data-return support would have been provided by Mars Global Surveyor (MGS).

The subjects of the orbiter relay capability[5-8], the hardware and protocols employed[9-11], and the teamwork and operational processes required to support these multi-mission efforts[12] have been covered in detail elsewhere. This paper will focus on the development, design, and planning necessary for a NASA mission to operate in an all-relay operational mode, without the safety net of a direct-from-Earth (DFE) emergency command capability, nor a direct-to-Earth (DTE) fault communications path.

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## II. Phoenix Landed Telecommunications Architecture

MSP ’01 was originally designed to communicate via UHF with MCO and Odyssey. Before the eventual cancellation of MSP ’01, the reviews following the failure of MCO and Mars Polar Lander[13, 14] resulted in augmenting the telecom design to have both UHF and X-Band communication systems. Recommendations included support of continuous communications during EDL, 2π steradian X-band coverage during the surface mission and a steerable X-band MGA for surface operations[14]. This configuration allowed for a more familiar X-band implementation of EDL critical event communications (a feature lacking from both MPL and Beagle, preventing confirmation of their suspected failure modes), with X-band “semaphores” implemented by both MPF and MER. The configuration continued through the proposal phase of Phoenix and past the project’s confirmation. Nearing the preliminary design review, several factors conspired for the return to the original MSP ’01 configuration of an all-UHF, relay-only landed communications architecture. Many design aspects related to the MSP ’01 program were never fully implemented before its cancellation, in addition, the Earth-Mars range for the Phoenix mission was greater, further stressing the communication link performance. Once on the surface, the data return requirements could not be demonstrated to be met with the X-Band system alone, thus creating reliance on single-string hardware in an otherwise block-redundant and single-fault tolerant architecture. With the demonstrated performance of the UHF relay link between the MERs and Odyssey and the addition of the MRO to the orbiting relays, a move back to the all-relay approach could be justified. Additional benefits included a significant mass savings on a lander beginning to be pushed to its limits, as well as a significant reduction in spacecraft implementation complexity. The architecture implemented for Phoenix is shown in Fig. 1.

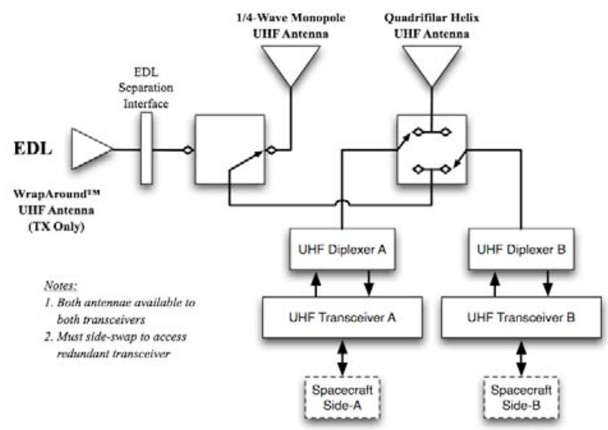


**Figure 1. Phoenix Landed Telecom Block Diagram**

## III. Relay Orbiter Support

The entirety of the Phoenix mission surface communication requirements will be satisfied through the use of both MRO and Odyssey. Memoranda of Agreement are in place with both programs to ensure resources are allocated and planning is conducted to support the Phoenix mission. In summary, the MRO mission (which will still be in its primary science mission phase) will plan support for two overflights per Sol[**] and Odyssey will support all overflights[††] with an elevation (as observed by the Phoenix lander) above 20°. For Odyssey, this amounts to as many as 6-7 opportunities to communicate with the lander per Sol, although nominally Phoenix only plans to use 2-3 overflights per Sol, combining the best opportunities from both MRO and Odyssey. While Phoenix is compatible with, and MER has made use of the MGS for return of data, Phoenix is not pursuing this capability due to the lack of its capability to forward-link spacecraft commands. MER also demonstrated compatibility with Mars Express (MEX) for both return data and forward commanding. Phoenix is considering this as a contingency-only option that would be pursued only in the event a significant issue arose on either of its prime orbiters, compromising the redundancy in communications links.

Phoenix is a stationary landed mission. In addition, the Phoenix lander will nominally control its azimuth to within a few degrees to the moment of touchdown (dynamics of landing may induce a pirouette effect, potentially perturbing it an estimated additional ±15°). Given this, once initial attitude is known and the UHF subsystem has been suitably characterized, predicts for the entire mission’s worth of communications opportunities can be made[15].

The exact timing of overflights is actually set no later than about eight weeks from Phoenix Entry Descent and Landing (EDL). In order to provide optimized communications coverage for the critical EDL events, both Odyssey and MRO will adjust their in-plane mean-anomaly such that they are both in the vicinity of the Phoenix landing site

[**] A “Sol” is one Martian day, or approximately 24 hours and 39 minutes on Earth

[††] An “overflight” is the term used to describe a single communications opportunity between the orbiting relay and the surface asset. The term “pass” is intentionally avoided to prevent communication with the DSN passes used by the orbiter to ultimately send the data back to Earth.

at the time of EDL. As such, the time of the overflights for the rest of the mission will be set by this initial epoch. Because of the differing orbital periods as well as the separated ascending nodes, it is infrequent that both orbiters will be overhead simultaneously. Outside of the initial dual-coverage of EDL, they will occasionally both be visible to the lander, and the frequency of this increases the more northerly the potential landing site. To ensure appropriate use of each of the orbiting assets, a strategic process[7] will be used to allocate and sequence support of Phoenix communications opportunities on each of the orbiters.

The analysis of the full mission communications coverage as described above has been performed for the purposes of performance estimation and verification of meeting mission requirements.

A side-effect of relay-only communication is the lack of need for direct support and coordination with the Deep Space Network (DSN)[16]. While Phoenix is certainly in need of this service and is sensitive to its performance, this infrastructure overhead is indirectly coordinated on behalf Phoenix by the orbiter programs.

## IV. Overflight Geometry and Background

Potential landing sites for Phoenix have been down-selected to a region in the northern polar region of Mars, centered on 67.5°N 130°E (site B1)[17]. Plots of pass duration as a function of a given local mean solar time for various horizon cut-off masks as well as orbiter elevation are shown in Figs. 2-5 [17]. Because of its northern-polar location, Phoenix will enjoy increased access to the orbiting-relays over what MER has experienced. While every orbit of Odyssey and all but two hours of MRO's orbits may at be visible from the Phoenix 67.5°N landing site, the low elevation (placing them in poor antenna pattern regions due to payload deck obstructions) and increased range will likely prevent many of these links from being utilized.

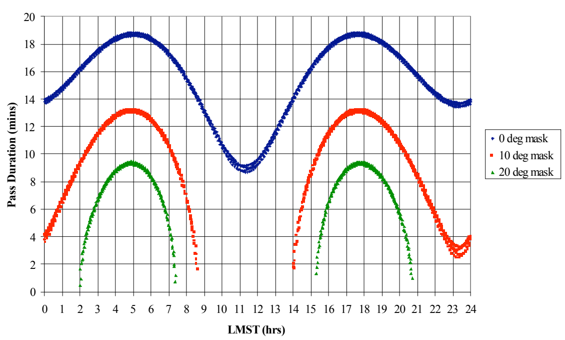


**Figure 2. Odyssey Pass Duration vs. Local Solar Time, Site "B1" 67.5°N**

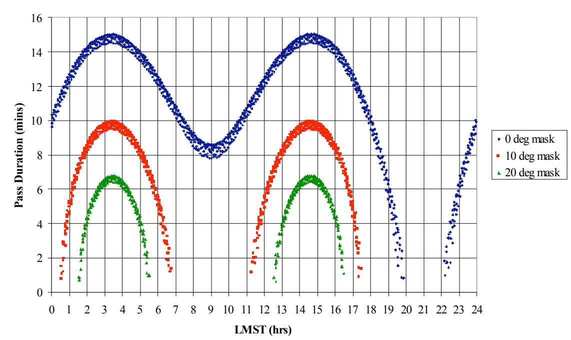


**Figure 3. MRO Pass Duration vs. Local Solar Time, Site "B1" 67.5°N**

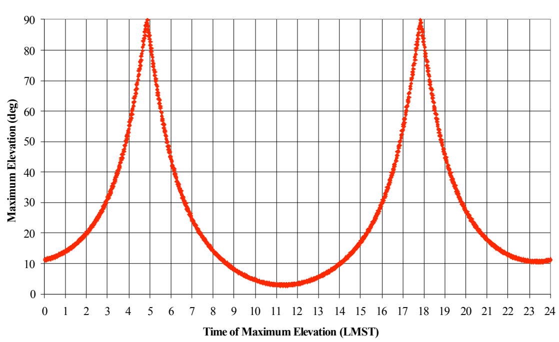


**Figure 4. Odyssey Max Elevation vs. Local Solar Time, Site "B1" 67.5°N**

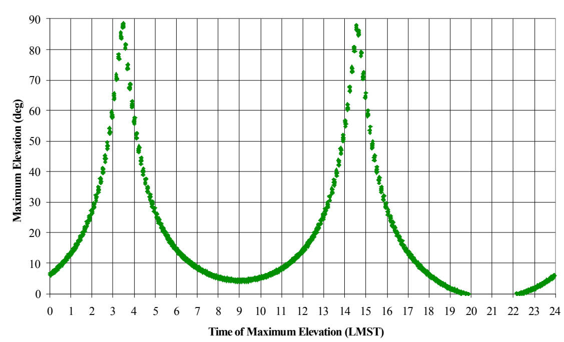


**Figure 5. MRO Max Elevation vs. Local Solar Time, Site "B1" 67.5°N**

# V. Relay-Only Impacts on Fault Protection Strategy

There are many aspects of DFE/DTE-based spacecraft interaction that the operations community has become accustomed to as a matter of typical practice. When examining a fault-tolerant communications approach for an all-relay mission, a number of notable adjustments are necessary.

## A. Relay Anomalies

When spacecraft communication depends on an intermediary, the intermediary's problems become the Phoenix operations team's problems. These range from anomalies on the relay spacecraft, to support by the DSN, and even include personnel issues on the relays' operations teams. The ideal communications and fault protection approach should be as insensitive to any of these problems as possible. A relay anomaly should not automatically induce an anomaly on the lander. One mitigating response is to include ample "run-out" activity sequenced on the lander should it not receive a command load for a given Sol, as well as something more than a "hair-trigger" uplink-loss response.

In addition to needing the lander to be fairly self-supporting for a short duration without ground interaction, the operations team should also plan for diversity in relay orbiter coverage, not placing all the relay responsibility on a given orbiter. Should a relay anomaly prevent its support of lander communications, the next alternate orbiter pass would allow for short-term or long-term adjustment of the lander communications strategy if needed.

## B. Spacecraft Fault Communications Rate

### *1. Control of Communications State*

A common practice for configuration of spacecraft during fault protection responses is to place the communications system in a known, safe, and robust uplink and downlink state. Often this will involve selection of one of the lowest supported data rates for both uplink and downlink, and typically the use of lower-gain and more omni-directional antennas.

With the use of the Proximity-1 protocol[9, 11], the orbiter will "hail" the lander and establish the configuration of the link without knowledge of the state of the lander. This may result in lander anomalies being discovered in a "nominal communications mode," with link rates typical for daily routine operations (128Kbps return rate, 8Kbps command rate). Instead of the trickle of data commonly accompanying a spacecraft in a faulted-state, Phoenix may have a wealth of data to aid in diagnosis of potential faults. This is an interesting paradigm shift, as it may often mean that the data management process necessary to keep the science data returning to ground operators will not necessarily be interrupted by "minor" spacecraft anomalies.

While high-data-rate fault communications may often be acceptable, there are situations were the operations team may prefer a lower communications rate, likely for one of two reasons: (1) The anomaly the spacecraft is experiencing is related to the communications subsystem itself, and the lower data rates may be necessary to achieve a robust link, or (2) the lower data rates will allow for more frequent opportunities to interact with the spacecraft, taking advantage of the lower-elevation, lower-margin overflights.

In order to achieve this change in relay configuration, *it is the orbiters* that must be commanded to change their state, not the lander. This configuration change will have to be accomplished after the ground detects a fault (by received lander data) or suspects a fault may have occurred (by lack of communications with the lander), and must be achieved within the turn-around-times that are possible with the latencies in operations decision processes, DSN passes with the orbiters, and upcoming relay opportunities with the lander. Alternate relay configurations are also discussed under Communications Failures below.

### *2. Command Screening*

An advantage of a spacecraft fault response which places the communications subsystem in an alternate fault communications state is that the command uplink rate can be used to screen commands which were intended for a non-faulted spacecraft. In this configuration commands transmitted to a spacecraft at a higher nominal rate will not be received by a spacecraft that is listening at a lower rate. The inverse is also true, and has its own advantages.

With a Proximity-1 link controlled by the orbiter, there is no corollary to achieving this "command-screening" by data rate alone. Because of this, Phoenix is modifying its flight software to indicate to the command and sequence engines when it is in a "safe mode," and the operations team must always check for this state when attempting to execute sequences that should not be executed if the spacecraft is in "safe mode."

The Phoenix implementation of this feature has its own advantages in that a single command load can be responsive to multiple-spacecraft states, without the need to reconfigure the command process and radiate separate command data for the possible spacecraft states.

## C. "Real-Time" Spacecraft Interaction

Interplanetary spacecraft operations must always accommodate the issues presented by round-trip light-time delays when interacting with a spacecraft. For complex or critical activities, there is often a desire to have "GO/No-GO" opportunities to confirm a spacecraft or instrument state, and then subsequently send a command in response to that state. While a relay-link does not necessarily prevent this type of interaction, in the case of Phoenix and its support by MRO and Odyssey, it prevents it from being practical. With orbiter overflight durations limited to no more than 16 minutes at most, and round-trip light-times to Mars being a minimum of thirty minutes during the Phoenix mission, a given overflight would be finished before the operations team had an opportunity to command a response. This is without even considering the overhead on preparing and radiating a command load to the orbiter, although special measures could be implemented to require only a single real-time-command to the orbiter to relay a pre-loaded on-board response. If Phoenix is to implement this capability, it would require stringing activities across several successive overflights (as available) and potentially across both orbiters. While this approach would provide the capability for "GO/No-GO" cycles it does so much less efficiently (in turn-around time) than a DFE/DTE link would provide for.

A side-effect of this condition is that for Phoenix, commanding is always "in-the-blind." In other words, the operations team can never be certain of the state of the spacecraft prior to sending commands. Measures such as the safe mode command screening described above are necessary to mitigate the potential negative impacts of this "feature."

## D. Commanding "In the Blind"

Due to the relay "feature" of always commanding in the blind, two things become of paramount importance:

*1. Unintended consequence of commands*

Given that the spacecraft could be in a different configuration than expected, constant awareness by the operations team is necessary to understand the potential effect of the commands they send. This not only includes the "safe mode" state previously mentioned above, but also possible faulted states for payloads and other hardware. For Phoenix, similar command-screening is implemented for the payloads, effectively creating a "safe mode" state for each, in order to prevent unintentional commanding from uplinked sequences.

*2. Deterministic behavior*

Keeping autonomous fault response timelines as deterministic as possible will aid in the spacecraft operations teams' ability to diagnose and respond to potential faults. Any state that may be asserted by on-board fault protection must be completely unambiguous and easily reproducible on the ground. While this is true for any spacecraft, it is even more important for a relay-only mission, where knowledge of the spacecraft state (i.e. awake and listening vs. asleep and not listening) is critical in order to properly plan relay passes. For this reason, a ground-in-the-loop downlink loss response (relying on continued ground notifications to execute a pre-planned sequence of telecom configurations) was abandoned for Phoenix, in favor of an uplink loss response that executed all possible configurations. This single uplink-loss behavior executes not only recovery strategies related to loss of uplink, but those related to loss of downlink as well.

## E. Communications Failures

*1. Scenarios*

Several references to the Proximity-1 protocol have been made thus far, and now the impacts of inability to achieve this link-method will be discussed. In a "two-way reliable link," everything must work, or nothing does. The inability of the radio to receive transmissions from the orbiter means that the lander will not receive the ACKnowledgment confirmation that its transmissions are being received. Likewise, if the lander is unable to successfully transmit data, the orbiter will not be able to send command data to the lander, as it would never confirm receipt.

Failure of either direction of the link at the UHF hardware level can manifest itself in two scenarios. A failure during an established link would result in both ends of the link repeatedly transmitting two Proximity-1 frames of data, never successfully getting ACK of successful receipt on the other side. A persistent failure (perhaps staying failed after the aforementioned failure mode) would prevent a new link from ever being established. The orbiter would attempt to hail the lander and establish the communication session and the lander would either not be able to hear the orbiter, or it would be unable to respond.

*2. Autonomous responses to failures*

If a failure of the telecommunications system is directly observable by the spacecraft (eg, the UHF transceiver fails to power up), the immediate response will be to access the redundant transceiver hardware. In the case of

Phoenix this means a series of resets and re-attempts which, if the failure persists, will quickly change the spacecraft over to its redundant side of hardware.

Less obvious failures may occur, and where they are not directly detectable by the spacecraft, it must eventually realize that “something is not working” and take similar measures to access the redundant hardware. The fault response implemented for this purpose is the often-used uplink-loss response. In this fault case the spacecraft has a configurable countdown timer that is reset by direct command. If the spacecraft operators fail to issue this command before the timer expires (either through unintended omission or the inability to command), the specialized uplink response is engaged until command capability has been re-established and the response is disabled.

In the unfortunate event that the failure mode is in the reliable link itself (either due to the lander or the orbiter), additional fault-tolerance can be added by augmenting an ultimate “safety net” mode in which the spacecraft will eventually attempt one-way, “unreliable” or open-loop links. The current Phoenix concept incorporates a cyclic pattern of receive-only, one-way transmit and reliable modes, through all available antennas.

*3. Ground responses to failures*

Unlike DFE/DTE controlled spacecraft, the spacecraft operations team must constantly prepare for faults, instead of simply responding to them when they occur. With limited opportunities for contacts between the orbiter and lander, any communications opportunities necessary for fault response must be planned for *in advance*. Both the orbiter schedule, as well as the on-board communications schedule must account for fault communications opportunities. Sequencing additional orbiter overflights will have no effect if the lander has not previously been configured to make use of them.

The first line of defense in Phoenix fault response design is to enact a communications schedule stored in an on-board table, periodically updated by the operations team. This table may include use of the “nominal” communications opportunities, or it may be adjusted to use more or less frequent overflight opportunities, depending on available spacecraft resources and preferences of the operations team. This strategy will be employed for most faults and will provide for minimal delay in recognizing and responding to a spacecraft fault.

*4. Dead-end behavior*

The failure to correctly synchronize the timing between the lander and orbiter communications periods is perhaps the most challenging situation to robustly design for, and typically represents “the end of the road” in mechanisms the spacecraft will employ in its efforts to re-establish communications. This disconnect between Phoenix communications attempts and orbiter availability may arise for several reasons: (1) A corrupted, improperly prepared or completely executed safe mode communications table, (2) substantial drift or loss of onboard absolute spacecraft time, or (3) substantial deviation in the orbital parameters of the orbiters. In response to these potential faults, Phoenix has chosen to implement a “fixed time-step” mode in which a configurable, fixed sleep-duration and wake-duration (listen) can be applied between successive communications attempts. The intent of this approach is achieve communications attempts at different local-solar-times on every attempt, eventually walking around the clock and landing on a time when an orbiter will be overhead. Doing this in a timely manner is significant challenge. For conservative worst-case assumptions with respect to performance of the telecommunications system, analysis has shown that contact with the spacecraft can be achieved within one Sol for a majority of the cases, but a few worst-case mis-alignments may cause recontact to take as much as one week or more. These cases represent a small percentage (less than a few percent) of all cases, and more nominal performance parameters reduce the severity of these outliers.

An alternative to the fixed time-step approach is to implement a mode in which the UHF transceiver is powered on in receive-only mode when the spacecraft is in a faulted state. The receive-only mode of the transceiver uses only 10% of the power that the transmitting mode requires, and the next time an orbiter is available, a communications session could be established. With the high heritage that Phoenix has from the MSP ’01 spacecraft design, implementation of this approach requires non-trivial architecture changes and the project is currently weighing the implementation risk of this approach against the acceptability of potential recovery delays introduced by the fixed time-step mode. The 2009 Mars Science Laboratory Rover is being designed from the outset to include this capability as well as some useful extensions to it.

## VI. Phoenix UHF Communications Test Program

The Phoenix program has implemented an extensive verification and validation program in order to ensure the successful operation of the lander in its use of the relays. This program began with testing of an engineering “Phoenix Lander Simulator” incorporating a C/TT-505 transceiver against the MRO flight spacecraft and its Electra UHF transceivers in the various modes that Phoenix plans to use in-flight. Thorough simulation and subsequent measurement of the approximate UHF antenna patterns attainable by the helix and monopole antennas were conducted at the SPAWAR antenna test range in San Diego, California. These measured antenna patterns were incorporated with margin into simulations of the expected in-flight performance of the telecommunication system to derive predicts for performance during the mission. In the assembly test and launch operations (ATLO) process of building up the Phoenix lander, the flight transceivers will be tested at several opportunities with not only orbiter simulators, but the actual spacecraft testbeds of Odyssey and MRO allowing for a "test like you fly" configuration that was not achieved for MER. Operational readiness tests with the spacecraft operations team and flight-like command and data configurations will prepare the staff for the nuances of relay operations described herein. Lastly, in-flight tests conducted by MER and Odyssey and potentially MRO on behalf of the Phoenix project will give further confidence in the performance of the system.

## VII. Challenges in Routine Operations

Forward and return link latency is governed by a number of variables ranging human and computer processing time to margin time for event boundaries, to the laws of physics and the speed of light. Part of the strategic communications processes[5, 12] will be to determine these latencies for all potential passes. The operations team must complete all of their present-Sol analysis and performance assessment activities, plan for the next Sol and uplink it to the relaying orbiter within these constraints. Whereas MER started with a 16 hour process, enabled-in-part by its DFE command capability and reduced latency, Phoenix will have to work within tighter constraints, starting at 14 hours, and trending downward as more activities are added to the day.

Due to the limited size of the non-volatile storage (16 MB) on the heritage Phoenix avionics, management of on-board data will be a daily challenge. A significant effort has been undertaken by the project system engineering staff to outline the necessary processes to ensure that the rate of data production is managed, and that all data is verified received-and-intact by operators before it is deleted from the spacecraft memory. This has limited the process to missing no more than two overflights without deleting old data before new data must be prevented from being generated.

## VIII. Special Considerations

Time synchronization of a spacecraft through a relay involves applications of technologies not yet demonstrated in flight[18]. In addition, these new protocols are not supported by the heritage UHF transceiver on-board the Phoenix lander. Phoenix has examined the performance of its hardware and the intial assessment is that the expected clock-drift during the 90 Sol prime mission (expected to be 40 seconds or less) is well within the timing requirements required to operate the mission. While certain fault scenarios may challenge this assertion, a number of techniques are available for both coarse (10s of seconds) and fine (seconds or less) exist, including direct commanding via carefully timed forward commands, to sequenced corrections based on observations of either the Sun or Mars' moons, Phobos and Deimos.

## IX. Conclusion

The Phoenix mission is well situated in the timeline of planetary exploration to take a significant step forward in routine surface operations via relay of command and data through orbiting spacecraft. The experience gained from prior missions including MER and Odyssey, the resources available to Phoenix in the form of well-tested relay assets, and attention to the unique needs of a surface relay-operated mission will ensure success in operating the Phoenix mission.

## Acknowledgments

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